Development of the Lidar Atmospheric Sensing Experiment (LASE) - An Advanced Airborne DIAL Instrument

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Abstract. The Lidar Atmospheric Sensing Experiment (LASE) Instrument is the first fully-engineered, autonomous Differential Absorption Lidar (DIAL) System for the measurement of water vapor in the troposphere (aerosol and cloud measurements are included). LASE uses a double-pulsed Ti:Sapphire laser for the transmitter with a 30 ns pulse length and 150 mJ/pulse. The laser beam is "seeded" to operate on a selected water vapor absorption line in the 815-nm region using a laser diode and an onboard absorption reference cell. A 40 cm diameter telescope collects the backscattered signals and directs them onto two detectors. LASE collects DIAL data at 5 Hz while onboard a NASA/Ames ER-2 aircraft flying at altitudes from 16-21 km. LASE was designed to operate autonomously within the environment and physical constraints of the ER-2 aircraft and to make water vapor profile measurements across the troposphere to better than 10% accuracy. LASE has flown 19 times during the development of the instrument and the validation of the science data. This paper describes the design, operation, and reliability of the LASE Instrument.

1 Introduction

Differential Absorption Lidar (DIAL) is a technique that is uniquely suited for making precise water vapor measurements in the troposphere [1,2,3]. Water vapor measurements made with the LASE instrument using the DIAL technique have been validated with results showing an accuracy of better than 10% for water vapor profiles across the troposphere [4]. No other instrument can provide the spatial coverage and accuracy of LASE. Water vapor is the most radiative active gas in the troposphere, and the lack of understanding about its distribution provides one of the largest uncertainties in modeling climate change. LASE has demonstrated the necessary potential in providing high resolution water vapor measurements that can advance the studies of tropospheric water vapor distributions.

LASE is a downward looking instrument that is flown aboard a NASA/Ames ER-2 aircraft at altitudes from 16-21 km. It weighs 520 kg and has a volume of approximately 1 m^3. The proven operating pressure is from standard atmosphere to 1/4 atmosphere and temperature is from 15° C to 40° C. After power is applied, the operation of LASE is totally autonomous. LASE can have continuous operation with data storage for the maximum ER-2 flight time of 8.5 hours.

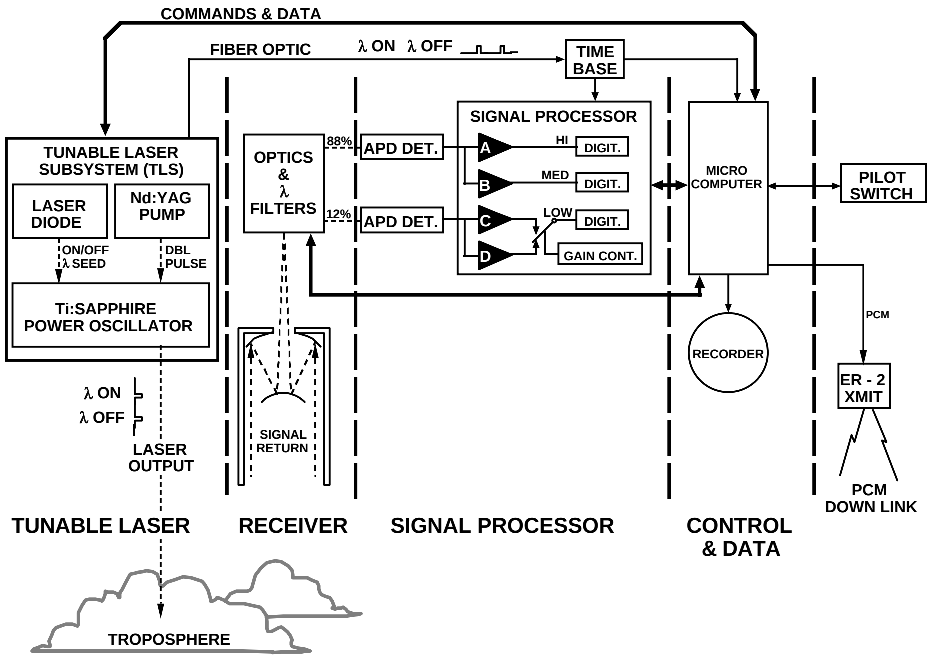

Fig. 1. LASE System Block Diagram

As shown in Figure 1, LASE is divided into four main parts: Tunable Laser Subsystem (TLS), Receiver Subsystem (RCS), Signal Processor Subsystem (SPS) and the Control and Data Subsystem (CDS). Each of these subsystems are discussed below.

2 Tunable Laser

The TLS was designed to operate in a double-pulse mode (separated by 400 μsec) at 5 Hz, with energy outputs of up to 150 mJ per pulse in the 813 to 819 nm wavelength region and with 99% of the output energy within a spectral interval of 1.06 pm. A Ti:Sapphire ($Ti:Al_2O_3$) power oscillator was constructed using a frequency-doubled Nd:YAG laser as the pump source and a single mode diode laser as an injection seeder for the $Ti:Al_2O_3$ laser [5,6,7].

In the laser schematic of Figure 2, a flashlamp pumped Nd:YAG laser delivers 1.4 J at 5Hz. It is doubled pulsed by a Q-switch into a highly deuterated CD*A second harmonic crystal which generates 530 mJ of 532 nm laser energy for pumping of the

Ti:Al_2O_3 power oscillator. The Ti:Al_2O_3 power oscillator produces output energies of 130 to 135 mJ at this pump energy level.

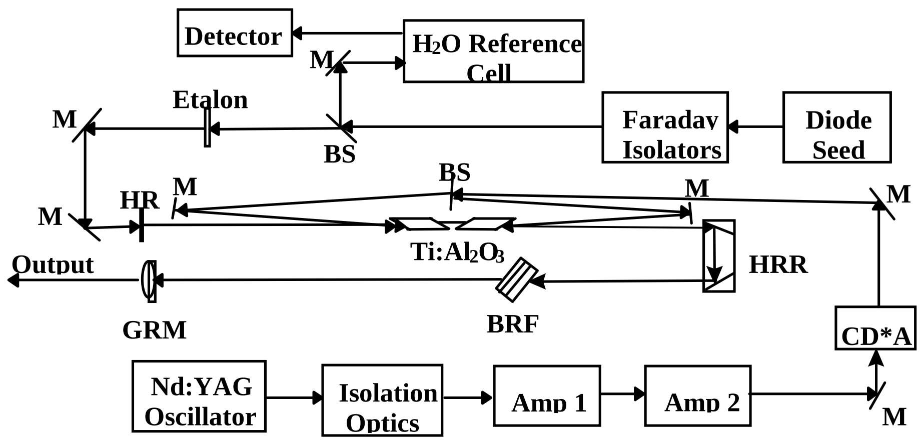

Fig. 2. Schematic representation of the LASE TLS optical layout.

The Ti:Al_2O_3 power oscillator cavity is an unstable resonator design [8] having a cavity length of 1.5 meters. Each of the two brewster cut Ti:Al_2O_3 rods has an active length of 18 mm. Other oscillator components include a graded reflective mirror (GRM) output coupler, a 97% reflective end mirror (HR), a four plate birefringent filter (BRF) to provide course control and narrowing of the output wavelength, and a hollow retro-reflector (HRR) which provides alignment insensitivity in the horizontal plane. The unseeded Ti:Al_2O_3 laser has a spectral linewidth of 1 nm and a tuning range which includes the required 813 nm to 819 nm wavelength region. The laser pulsewidth is 30-40 ns FWHM and is dependent on the pump energy fluence. Its beam diameter is 3.2 mm (at $1/e^2$) with a beam quality of 1.3 times diffraction limited. Fine linewidth and wavelength control of the Ti:Al_2O_3 laser is achieved by using the output of a single mode diode laser as an injection seed source [9]. The diode seed beam is a continuous wave of 100 mW and is injected through the 97% HR end mirror. Typically 1 mW of seed power is transmitted into the power oscillator cavity. Injection seeding allows control of the spectral linewidth to less than the required 1.0 pm and provides wavelength stability to better than +/-0.25 pm as measured using a high finesse Fabry-Perot Interferometer. Injection seeding also achieves the LASE spectral-purity requirement of maintaining greater than 99 percent of the laser output energy within a 1.06-pm interval. Spectral purity was measured using the absorption-to-transmission ratio of laser pulse through a 200m path length water vapor filled cell. To achieve this required spectral fidelity, the diode laser wavelength is locked onto a preselected water absorption line feature by passing a fraction of its frequency modulated light through a multipass reference cell filled with water vapor and detecting the cell transmission of the light. By detecting the null of the transmitted light, the diode wavelength can be locked onto the absorption feature. Electronic feedback control of the diode temperature and current serve to maintain the diode’s wavelength line-locked to the feature. Typically, 3 mA/pm is the control law rate for the feedback in controlling the wavelength. The current can be adjusted in 1 uA increments. The tunable diode laser seeds the pulsed laser alternately between "on-line" wavelength, the first pulse of the pulse pair, located at the center of the water vapor line and "off-line" wavelength, the second pulse of the pulse pair, typically located 20 to 80 pm away from the "on-line" wavelength. The "on-line" and "off-line" wavelengths are measured to within +/-1pm using a wavemeter. The accuracy of the "on-line" wavelength is verified by comparison to the line-locked wavelength of the diode and is further validated by spectral purity measurements. Ninety (90) db of isolation between the diode and the $Ti:Al_2O_3$ HR end mirror is used to prevent pulsed $Ti:Al_2O_3$ energy feedback to the diode laser. Laser energy feedback to the diode could cause diode damage and mode-hopping. A 150 μm thick etalon is used to suppress any side bands of the diode laser output before it enters the $Ti:Al_2O_3$ resonator where it would decrease spectral purity.

A new diode seeding technique was developed to enhance the capability of the LASE instrument [10]. The strong vertical absorption gradient of atmospheric water vapor had required the LASE measurement to typically use a strong water vapor line to detect low concentrations of water vapor at high altitudes and weak water vapor lines to detect much higher concentrations at lower altitudes. Operationally this has meant recording high altitude water vapor profiles over a predetermined aircraft ground track in one leg of a flight and then retracing this ground track in a another leg of the flight to record low altitude water vapor data. The new multi-wavelength sequential diode seeding approach uses a wavelength that is accurately positioned (to within 0.1 pm) on the slope of a strong water vapor absorption feature, hence, enabling the accurate selection of the size of absorption cross-section to be probed. This slope position is accomplished by a precise current pulse to the diode that has been characterized. The new approach allows a single strong water vapor line to be used to probe both the higher and lower altitudes along a single ground track. In a repeating sequence, a pulse pair of "on-line" and "off-line" (which probes high altitude water vapor) alternates with a pulse pair of "side-line" and "off-line" (which probes the lower altitude water vapor). In this way nearly simultaneous measurements of the atmosphere from sea level to about 14 km are accomplished along a single ground track.

3 Receiver

The LASE RCS telescope is a mechanically and thermally stable F/21 Dall-Kirkham design. The barrel of the telescope is graphite-epoxy and designed to maintain the separation of the primary and secondary mirrors, over the LASE operating environment, to within 25 μm for longitudinal stability. The telescope optics are light-weighted Zerodur for thermal stability with an 800-cm focal length, a 0.1 m^2 collecting area, and a continuously adjustable field of view from 0.15 mrad to 3.0 mrad.

The RCS aft optics are polarization insensitive and include an interference filter that is actively tilt-tuned to the desired water absorption line wavelength. The received light is split for three output channels: an engineering channel and two science channels. The engineering channel uses a 20 mm diameter silicon quad detector for measuring the laser-to-telescope alignment. A 1.5-mm diameter silicon avalanche photodiode detector (APD) is placed at the focus of each of the two optical science channels. The aft optics layout is shown in Figure 3. A microprocessor based Receiver Control Unit controls and monitors all of the electro-mechanical functions including the shutter, field-of-view, and tilt-tuning filter.

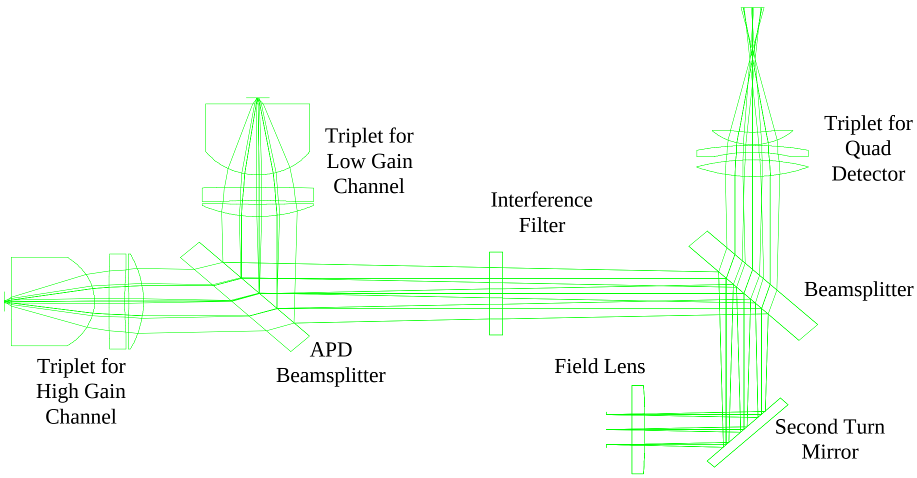

Fig. 3. Aft Optics Layout (First Turn Mirror not Shown)

The light enters the aft optics through the primary hole and is folded into the plane of the aft optics using a turn mirror. A shutter and adjustable field stop (not shown) are placed at the telescope focus. The shutter is periodically closed for background electronic noise measurement and calibration. The field-of-view is adjusted using an iris mounted in a rotary stepper motor. Approximately 1 percent of the light is directed to the quad detector channel. The field stop is imaged onto the quad detector for ground alignment of the laser to the telescope. The remaining 99 percent of the light passes through one of two interference filters designed to reduce background light levels. The light is then split at the APD beamsplitter in order to increase the dynamic range of the system; 11 percent is reflected to the low-gain APD channel and 85 percent is transmitted to the high-gain APD channel. The beamsplitter is polarization insensitive and slightly wedged. A uniform image at the APDs is obtained by imaging the telescope entrance pupil onto the APD with a triplet lens.

The Receiver contains two interference filters mounted on a rotation stage. One filter is used for day and the other for night missions. The typical day filter has a peak transmission of 0.48 and a full width haft maximum (FWHM) bandwidth of 350 pm. The peak transmission of a typical night filter is 0.65 with a FWHM of 990 pm. The selected filter is tilt-tuned to the desired laser wavelength and is adjusted to compensate for ambient temperature changes. The filters are used in uncollimated light, with a half cone angle of 1.3 degrees and a 0.35 degree obscuration, that is uniform with incident angle. The filter throughput is a function of the filter center wavelength, the effective index of refraction, the wavelength of incident light, the incident angle, the filter tuning angle, and the filter bandwidth.

4 Signal Processor

The light signals from the RCS are converted to electrical signals at the APDs, which are followed by transimpedance amplifiers. Each APD and amplifier is housed in a detector preamplifier unit (DPU) in the SPS (Fig. 1). The low gain DPU maintains constant responsivity over the operating temperature range by actively adjusting the APD bias voltage. Because the high gain DPU is more noise sensitive, low noise and constant responsivity are maintained by cooling its APD to a controlled set temperature of 12 degrees Celsius while applying a fixed bias voltage. The responsivity of each of the DPUs was nominally set to 75 amps per watt at the operating wavelengths. The responsivity was determined as a compromise between the effects of a high responsivity, resulting in an undesirable high excess noise factor at high signal levels, and a low responsivity, resulting in an undesirable high noise equivalent power at low signal levels. The bandwidth of each of the DPUs was nominally set to 2.5 MHz.

The electrical outputs of both DPUs enter the differential inputs of the Signal Processing Module (SPM) to receive further amplification and filtering. The two SPM inputs are electrically split in order to further increase the dynamic range. The high gain DPU output is split into channels A and B, and the low gain DPU output is split into a switch selectable channel C or D. Before leaving the SPM, all three output channels pass through a 1.5 MHz Bessel filter, to set the system analog bandwidth, before entering their respective 12 bit digitizer. The digitizer conversion speed is 5 MHz which exceeds the Nyquist sampling criteria. The LASE Coherent Timebase provides the digitizer clock and trigger pulses which synchronize the digital output of the three science channels.

5 Control and Data

The operation and data acquisition of LASE is controlled by the CDS subsystem. The basic functions are coordinated by internal commands through the control states of 2 modes and 3 submodes. The modes are STANDBY and OPERATE. The submodes are WAIT, TUNE, and DATA. After the LASE Instrument receives power during preflight, the initial command is STANDBY:WAIT. The instrument is held in this state while the aircraft climbs to altitude, during which time the laser cavity temperature is stabilized. Safety inter-locks and a pilot switch have to be satisfied before LASE can advance out of this state. When the ER-2 is at operational altitude, a pilot switch will activate the OPERATE state. The TUNE submode begins the scanning of a pre-selected water-line with the seeding diode laser. The scan consist of a coarse and fine scan to ensure an acceptable lock on the water-line. When the scan analyses are complete, the submode switches to DATA. At this time the Nd:YAG pump laser flashlamps begin flashing with a delayed Q-switch for pre-conditioning of the optics. The timing of the Q-switch is gradually shifted to maximize laser beam energy. The SPS is synchronized to the return signals by the time base module when the laser pulse leaves the instrument. After storing the return signals from the first laser pulse, the second laser pulse is emitted (400 μsec after the first). The digitization of this second set of return signals completes the cycle for one DIAL data sample. The LASE Instrument repeats this operation at 5 Hz throughout the mission. LASE will return to STANDBY on deactivation of the pilot switch or the altitude interlock switch. The CDS monitors engineering parameters from the instrument, comparing each to a set of limit conditions. When an irrecoverable limit is exceeded, the CDS will return the instrument to STANDBY and, through a FAIL light, inform the pilot to return to base. For more critical limits, the CDS may remove power from one or more subsystems, including, if necessary, its own power.

The CDS controller is built into a CAMAC crate using off-the-shelf microprocessor and data-acquisition modules. The unique hardware functions were built in-house to be CAMAC-compatible. The CDS data recorder is a single-board-computer PC-based system using two 1-Gbyte off-the-shelf hard disk drives. The disk drives are contained in a pressure canister to allow high-altitude operations. Total recording time is 9.5 hours. When flights are within a 230 mile range, a down-link of the LASE data stream to the ground station is made possible using the RF transmitter aboard the ER-2 aircraft. This allows the processing of LASE water vapor and aerosol data for real time experiment control.

6 Summary

LASE is an advanced lidar instrument that is fully engineered to meet the requirements of making precise DIAL measurements of water vapor for the total column in the troposphere. The LASE Instrument has successfully completed extensive characterization in the lab and validation testing in the field. LASE is self-calibrating and does not need external reference data to obtain accurate water vapor measurements.

In addition to collecting science data for NASA's Mission To Planet Earth Program, LASE will be used as a testbed to demonstrate advanced airborne and spaceborne DIAL technologies. These advancements will include new lasers, detectors and receivers for developing the first generation of spaceborne DIAL instruments.

7 Acknowledgments

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